Erosion and sediment yield from a landing failure after a moderate rainstorm, Tairua Forest

A.J. Pearce and P.D. Hodgkiss

ABSTRACT

A rainstorm of a size likely to occur once every 1.5–2.0 years caused substantial erosion of a recently formed log landing. Sediment yield from the catchment affected was 3000 times larger than from an adjacent catchment during the storm. Sediment yields from subsequent storms were higher than from the adjacent catchment by factors of 30-80, 2-7 and 15, respectively, for the 1st, 2nd and 3rd years after the storm which caused the erosion. Avoiding hazardous sites for landings, or modifying construction and harvesting techniques to reduce the impacts of fill failures if hazardous sites cannot be avoided, are identified as essential ingredients of good harvest planning. Steep slopes leading directly into streams are particularly hazardous because fill failures are likely to create debris slides or flows which will transport large volumes of sediment into streams. Fill compaction and drainage of landings and roads leading onto landings are essential components of good landing construction.

Many studies of erosion caused by forest harvesting have shown that roads and log landings are the largest and most common sources of sediment. Another common finding is that essentially all the sediment comes from one, or a few, isolated and superficially minor sources. Often these sediment sources are failures of landing or road (sidecast) fill. Here we describe how a single landing fill failure, at first glance small and insignificant, dramatically increased sediment yield and degraded physical water quality. The example we describe was triggered by a moderate storm, of a size expected every year or so, not by a "freak storm" or "act of God". As we show in this case study, the impact of a single failure can persist for several to many years because sediment placed in storage in the stream system continues to be available to the stream. Even if the source area is repaired, it is usually not possible to remove sediment from the stream system without causing more damage. Thus, prevention and avoidance of such incidents are essential features of good logging planning and practice.

STUDY SITE AND METHODS

In late 1982 and early 1983, one log landing c. 2500 m^2 in area, a second landing c. 4000 m^2 in area, 720 m of new logging road and 200 m of upgraded road were formed in a previously undisturbed 23 ha catchment planted in mature *P. radiata*, Cpt 114, Tairua Forest. These earthworks were in preparation for logging of an experimental catchment which had been monitored for streamflow and sediment discharge since January 1978. In mid-April 1983, before the landings had been surfaced with gravel and before any forest was felled, a moderate rainstorm caused substantial erosion of one edge of the larger landing (Fig. 1). Mass failures and gully erosion of the landing fill supplied sediment to a small debris flow which entered the channel of the monitored stream and caused substantial deposition for more than 500 m downstream (Figs 2, 3, 4). Sediment eroded from the landing fill and stored in the stream channel was estimated using distance, depth and slope angle measurements.

The authors: Andrew Pearce, Scientist, Forestry Research Centre, FRI, Christchurch; Pat Hodgkiss, Technical Officer, Forest Research Institute, Rotorua.

Figure 1 Eroded landing fill edge shortly after April 1983 storm. Figure indicates depth of gullying in coarse uncompacted fill.

Figure 2 Sediment stored in small terraces on stream channel approximately 200 m downstream from landing failure.

Two recording raingauges are located at the lowest elevation and near the highest elevation of the study catchment, and streamflow from the catchment is measured at a V-notch weir. Sediment storage is measured in the concrete stilling pond of the weir by regular emptying and weighing. A smaller (3.2 ha) control catchment similarly monitored for streamflow and sediment is partly adjacent to the catchment affected by the landing failure, but was unaffected by the landing erosion. Streamflow and sediment data from the control catchment were compared with those from the larger catchment to assess the impacts of the landing failure.

PRE-STORM CONDITIONS AND MAGNITUDE OF APRIL 1983 STORM

Rainfall during January to March 1983 was light at both recording gauges in the study area; 120 mm fell at the lower elevation gauge and 170 mm at the upper gauge. The March rainfall mainly occurred in a single six-hour storm totalling 41 mm at the lower gauge and 47 mm at the upper gauge.

Maximum one-hour rainfall in this storm was 15 mm at both gauges. Streams were dry before this storm and flow recommenced during the storm. On the 23 ha catchment, flow persisted for nine days after the storm, but only for one day on the 3 ha catchment. Small rainfalls in early April re-establishd flow at extremely low levels.

On April 18-20 and April 22, 195 mm of rain fell at the lower elevation gauge and 260 mm at the upper gauge. Rain fell in three distinct periods during the storm. Maximum rainfall amounts for various durations are shown in Table 1, together with return periods for these amounts of rain estimated from tables and maps in Tomlinson (1980).

The return period of these rainfall amounts barely exceeds two years for the shortest durations and is generally about 1.5 years. Such rainfall amounts have a probability of 50-67% of occurring in any year. During 1978-83, one-day rainfalls greater than that in the April 1983 storm occurred on five days, slightly less frequently than once a year on average.

STREAMFLOW RESPONSE

On the 23 ha catchment, streamflow increased to 2.3 mm/hr, 4.8 mm/hour, and 3.9 mm/hour peak runoff rates in response to the three periods of rain during April 18-22. The highest of these rates was exceeded eight times in the previous five-year record, so peak runoff rates of this level typically occur more than once a year. The highest peak flow rate of 15.7 mm/hr recorded before April 1983 is 3.3 times greater than the peak runoff rate from the April storm.

On the 3 ha catchment, streamflow increased to 1.4 mm/hour, 2.8 mm/hour, and 2.2 mm/hour in response to the three periods of rain. The highest of these rates was exceeded 10 times in the previous five-year record. The highest peak flow rate of 13.7 mm/hour recorded before April 1983 is 4.9 times greater than the peak runoff rate from the April storm.

The moderate streamflow responses to the April 1983 storm emphasize that it was not large or particularly intense.

LOCATION AND VOLUMES OF DEBRIS ERODED

As a result of the April 1983 storm, the northern edge of the fill forming the larger landing (on the south boundary of the 23 ha catchment) was seriously eroded in two places by both gullying and mass failure. At these places the fill was more than 10 m thick and was poorly compacted. The fill slope was often steeper than 40°.

About 20-40 m^3 of fill was eroded from the north-eastern edge of the fill, mainly by gullying. Gentle slopes (about 15°) below the fill ensured that most of this eroded material was deposited on the forest floor about 15-20 m downslope of the landing. Sediment from this area of fill erosion apparently did not enter the stream system in any significant quantity.

At the centre of the north side of the landing, where fill was particularly thick in the head of a drainage depression, between 180 and 260 m^3 of fill was eroded by mass failure and gullying (Fig. 1). Immediately downslope of the fill edge, the eroded material transformed into a debris flow. Considerable volumes of water from both the landing surface and a 70 m-long segment of road draining onto the landing must have mixed with the eroded debris to form the debris flow, because slopes below the landing are not particularly steep (20-25°). Gullying to depths of 1.5-2.0 m occurred in the fill along at least 30 m of the landing edge, confirming that large volumes of water flowed over this part of the fill edge.

The debris flow travelled about 150 m downslope and scoured the forest floor to a depth of 75 cm in a few places, but generally was not erosive except for the last 30 m above the point of entry to the stream draining the 23 ha catchment. At this point, 50-70 m^3 of soil and rock was scoured from the hillside. Little deposition occurred on the slope between the landing and the stream, except as flow levees and sediment piled up to 30 cm deep upslope of trees. The largest boulder transported by the flow was about 85 cm x 70 cm x 50 cm, and probably weighed about 400-500 kg.

The estimated volume of material eroded from the landing fill and the hillslope which could have entered the stream channel of the larger catchment is between 230 and 330 m^3. No signs of mass erosion or stream channel erosion were apparent in the adjacent 3 ha catchment as a result of the storm.

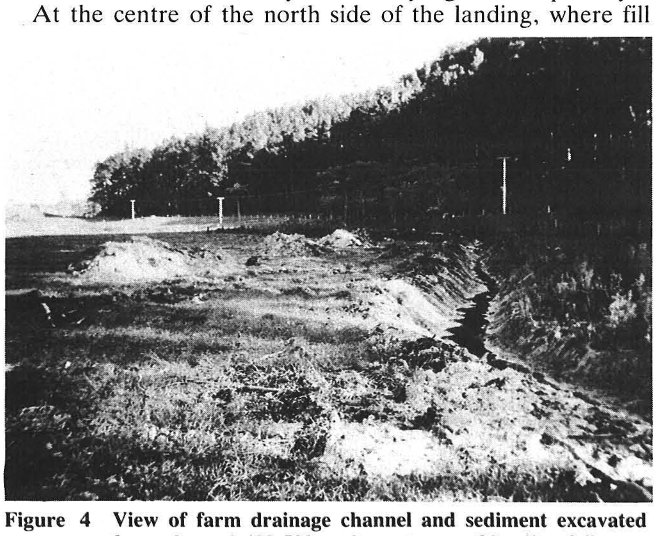

Figure 4 View of farm drainage channel and sediment excavated from channel 400-500 m downstream of landing failure.

Figure 3 Sediment deposited in neighbouring farm's drainage channel approximately 400 m downstream of landing failure.

LOCATION AND VOLUME OF DEPOSITS SHORTLY AFTER THE STORM

At the point where the debris flow entered the stream, about 20 m^3 of sediment was deposited in a pool in the stream channel. The largest boulder deposited here was about 70 cm x 50 cm x 40 cm, weighing about 225 kg. No deposits were found upstream of the point of entry. For about 350 m downstream of the entry point, as far as the monitoring weir, sediment had filled the channel to maximum depths of 60 cm, but much of this sediment was flushed out of the channel as streamflow fell after the rain ceased (Fig. 2). Narrow terraces about 20 cm wide and 10-50 cm high were formed along much of the channel. Between 40 and 80 m^3 of fresh sediment were estimated to be stored in these terraces, and another 5 m^3 within the stream channel immediately above the weir stilling pond.

The stilling pond of the weir was completely filled during the storm, and 17 m^3 of sediment were subsequently excavated. Below the weir the stream is culverted under Opoutere Road to flow across farmland in a drainage ditch. Some 70 m^3 of sediment were estimated to have been stored in the drainage ditch upstream of a small culvert pipe which became blocked by sediment during the storm (Figs 3, 4). Deposition on pasture surrounding the blocked culvert was estimated to amount to a further 100 m^3. Deposition in mangrove swamp in the tidal zone of Wharekawa Harbour at the mouth of the stream/drainage channel, some 500 m downstream of the landing failure, was estimated to be at least 15 m^3. In total, the estimated volume of deposits was about 265-300 m^3, accounting for most of the estimated volume eroded from the landing and hillslope. Of the total volume of deposits, at least 200 m^3 was exported from the 23 ha catchment during and immediately after the storm.

EROSION RATES AND SEDIMENT YIELDS

Based on the estimated eroded volume, the erosion rate on a whole-catchment basis for this storm was 10-14 m^3/ha. If the erosion is referred only to the total area of road and landings (about 1.05 ha), however, the erosion rate was about 220-315 m^3/ha. This erosion rate lies near the upper end of the range of recorded erosion rates from forest roads, using data from surveys over periods of several years, and is in the middle of the range of erosion rates on forest roads caused by storms with large (10-50 years) return periods (Sidle *et al.* 1985, Tables 10a and 10b). Expressed as a sediment yield, the volume of sediment exported from the 23 ha catchment during the storm was about 9 m^3/ha.

The stilling pond of the 3 ha control catchment was drained and emptied immediately after the storm and was found to contain 14 kg of inorganic sediment (about 0.01 m^3). The sediment yield was 0.003 m^3/ha, about 3000 times smaller than that from the catchment affected by erosion of the landing fill.

SEDIMENT TRANSPORT MID-1983 TO MID-1986

During the first three years after the landing failure, sediment outputs from both catchments were measured by cleaning out the sediment traps on five occasions. Four of the cleanouts were shortly after storms of similar size to the one which caused the initial erosion. The last cleanout was shortly after a similar-sized but more intense storm, and four smaller storms had occurred during the preceding 10 months. Organic matter content was determined for subsamples and only inorganic sediment yield is reported in Table 2. Suspended sediment yield during and between the storms was not successfully monitored and is not included in the sediment yield totals.

Rainfall totals in the 10 largest storms during the three-year period did not exceed those in the April 1983 storm, except for one storm in December 1983 which had a rainfall total at the upper gauge 30 mm larger than that in the April storm. In several of the storms between mid-1983 and early 1986 amounts of rainfall in periods from three hours to one day were greater than those in the April 1983 storm. Maximum rainfall amounts for any duration between one hour and three days in any of the storms during the three-year study period had return periods of two years or less, similar to those in the April 1983 storm (Table 1).

TABLE 1: RAINFALL AMOUNTS FOR VARIOUS DURATIONS, APRIL 18-22, 1983

Duration	Rainfall amount Lower Gauge	Rainfall amount Upper Gauge	Return period (years)
1 hour	32 mm	32 mm	2.2
2 hours	42 mm	44 mm	2
6 hours	55 mm	72 mm	1.1 – 1.5
12 hours	86 mm	103 mm	1.2 – 1.5
1 day	91 mm	109 mm	1 - 1.2
2 days	140 mm	185 mm	1.2 - 2
3 days	143 mm	190 mm	1.2 - 1.8
4 days	189 mm	256 mm	outside range of estimates based on Tomlinson (1980)

TABLE 2: SEDIMENT YIELDS FOR FIVE PERIODS MID-1983 TO MID-1986

Period	Sediment yield (excluding suspended sediment)[1] 3 ha catchment	23 ha catchment	Ratio 23 ha/3 ha
28/4/83 to 17/11/83	188 kg (0.04 m^3/ha)	15-30 m^3 (0.65-1.3 m^3/ha	16-32
17/11/83 to 20/12/83	183 kg (0.04 m^3/ha)	15-75 m^3 (0.65-3.25 m^3/ha)	16-81
20/12/83 to 14/9/84	47 kg (0.01 m^3/ha)	2405 kg (0.07 m^3/ha)	7
14/9/84 to 11/4/85	287 kg (0.06 m^3/ha)	4365 kg (0.13 m^3/ha)	2
11/4/85 to 28/2/86	117 kg (0.025 m^3/ha)	8 m^3 (0.35 m^3/ha)	14

[1] Masses converted to volumes at 1500 kg/m^3 density.

Peak streamflow response of both catchments during several of the storms was larger than that in the April 1983 storm, partly because of wetter conditions before the rainstorms, and partly because of higher rainfall rates over periods of three hours to one day in some storms. Peak runoff rates ranged up to 8.1 mm/h on the 3 ha catchment and up to 8.4 mm/hr on the 23 ha catchment during the February 1986 storm, which had the highest rainfall rates for six-hour to 12-hour durations during the study period. In both catchments the flow rate was 55-60% of the maximum peak flow observed during the period 1978-1986.

Sediment quantities yielded from the 3 ha catchment ranged from 0.03 m^3 to 0.2 m^3 (Table 2). From the 23 ha catchment, sediment quantities ranged from 1.6 m^3 to 15-75 m^3 in corresponding periods. The sediment trap on the larger catchment overflowed during the two storms in November and December 1983. In these two events, minimum sediment outputs were 15 m^3 (sediment trap volume); estimated maximum volumes of sediment were 30 and 75 m^3 for the November and December storms, respectively. The ratio of sediment yield from the catchment affected by the landing failure to that from the unaffected catchment was in the range 16-80 for the two storms in late 1983. The ratio decreased to 7, and then to 2 during 1984 and early 1985, and then increased again to 14, averaged over four smaller events from mid-1985 to January 1986 and the more intense event in February 1986. Mean sediment yield over the three-year period from the catchment affected by landing erosion was between 0.6 and 1.7 m^3/ha/year compared with 0.06 m^3/ha/year from the unaffected catchment.

CAUSES OF THE APRIL 1983 DAMAGE

The amounts of erosion and sedimentation caused by the April 1983 storm are excessive for the magnitude of the storm. If every storm of such size caused similar damage, then road and landing-related erosion at Tairua Forest would be approaching extreme levels, and this is not generally so. Other factors must have been involved in the extent of damage to this particular road and landing. One probable factor is poor compaction of the fill material, combined with the great thickness of fill in this particular landing. Landing edges were built up to slopes that were too long, too steep, and barely stable. Low moisture content of the fill, caused by the extended dry period during and before construction, probably made the fill difficult to compact properly. Water runoff from 70 m of road leading down onto the landing surface also contributed to the failure by providing additional water to that from the large (4000 m^2) landing surface itself. Spillover of the surface runoff from the landing and road onto the very steep fill edges was the primary cause of gullying, and, eventually, saturation of the fill edge caused mass failure.

SUMMARY

1. Gullying and mass erosion of a landing fill during a moderate storm increased the sediment yield of the affected catchment by about 3000 times compared to that of an adjacent, unaffected catchment.
2. Between 30 and 130 m^3 of sediment remained readily available for removal by the stream after the storm, a volume sufficient to supply several to many years of normal sediment yield.
3. Between 40 and 120 m^3 of temporarily stored sediment was exported from the catchment over the three-year period after the storm.
4. Increases in sediment yield caused by the landing erosion declined from 30-80 fold to 2-fold over the first two years after the storm, but increased again to 15-fold in a more intense storm with higher peak runoff rates at the end of the third year.
5. The effects found in this study are similar to those of many other studies of road and landing erosion in that one or a few small mass failures greatly change the sediment yield and water quality of small catchments for periods of years or longer.
6. Identification of sites where such mass failures are likely to occur is an essential ingredient of good harvest planning.
7. Avoiding hazardous sites, or modifying construction and harvesting techniques to reduce the impact of fill failures if such sites cannot be avoided, are the keys to minimizing the impacts of logging on sediment yield and water quality. When problem sites cannot be avoided, proper fill compaction and drainage of surface runoff away from thick fill edges are essential.

ACKNOWLEDGEMENTS

Successive Officers-in-Charge, Tairua Forest, have provided assistance to this study, and forest staff, especially Brian Jones, have carried out all the normal servicing of the instruments and weirs. Staff of Forest Land-Use Impacts (formerly Geohydrology) and Soils and Site Amendment research fields of FRI, especially Bill Dyck, have contributed in numerous ways to the long-term project of which this study forms part.

REFERENCES

Sidle, R.C.; Pearce, A.J.; O' Loughlin, C.L. 1985. Hillslope stability and land use. Water Resources Monograph 11. American Geophysical Union. Washington DC. 140pp.

Tomlinson, A.I., 1980. The frequency of high intensity rainfalls in New Zealand, Part 1. Water and Soil Technical Publication 19. Ministry of Works and Development, Wellington. 36 pp.

RECOMMENDATIONS FOR MINIMIZING ROAD AND LANDING EROSION

- Avoid hazardous sites if possible and adopt low-impact construction and harvesting techniques when hazardous sites cannot be avoided.
- Preventing damage to newly constructed landings and roads requires close attention to fill compaction and construction of fills with edge slopes that are less steep than the example in this paper.
- Reducing the area of landings to a practicable minimum, will assist in reducing the amount and thickness of fill.
- Avoiding road sections leading down onto landings will minimize saturation of the landing fill and spillover of surface runoff. Where necessary, effective cutoffs or culverts must be installed to lead water away before it encounters erodible fill.
- Reconnaissance of the terrain surrounding proposed landing areas, especially where large landings are planned, where fill thicknesses will be greater than normal, or where adjacent slopes are steep, will help in assessing the consequences of landing-fill failures, should they occur.
- Particular care is needed where landing fills are placed on steep slopes leading directly into streams. Thick fills on such sites should be avoided if at all possible because any failure of the landing fill is highly likely to create a debris slide-avalanche-flow which will transport a sizeable volume of sediment directly into the stream.
- Methods of minimizing fill thickness on hazardous sites include the use of stepped landings and end-hauling spoil to more stable sites. Complete avoidance of the potential problem by using another site for the landing should also be considered.

CONSULTANT RECOGNITION

Mr G.P.S. Allan, West Coast, has applied for recognition as a General Forest Consultant.

Under the NZIF Constitution any member of the Institute may send objections in writing to the:

Registrar of Consultants,
NZ Institute of Foresters,
P.O. Box 12314,
WELLINGTON NORTH